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TECHNOLOGY PROGRAM
PROGRESS REPORT NO. 41

October, November, December
1979

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CONTENTS

INTRODUCTION AND SUMMARY	vii
<u>1.0 PART ONE: DOE TASKS</u>	1
1.1 THERMIONIC AND MATERIAL RESEARCH AND TECHNOLOGY	1
1.1.1 TASK I. SURFACE AND PLASMA INVESTIGATIONS	1
A. Surface Characterization Chamber Experiments..	1
B. Converter Theory	7
1.1.2 TASK II. LOW-TEMPERATURE CONVERTER DEVELOPMENT	15
A. Converter No. 215: Heat Flux Diode: Tungsten Emitter, Nickel Collector	15
B. Converter No. 225: CVD Tungsten (As Deposited) Emitter, Nickel Collector	26
C. Converter No. 226: CVD Electropolished Tungsten Emitter, Nickel Collector	26
1.1.3 TASK III. ENHANCED MODE CONVERTER EXPERIMENTS	32
1.1.4 TASK IV. COMPONENT HARDWARE DEVELOPMENT	34
A. Alloy Hot Shell Development	34
B. CVD Hot Shell-Emitter Development	36
C. Integral Cesium Reservoir Converter No.222: Tungsten Emitter, Nickel Collector, Cesium-Graphite Reservoir	40
1.2. THERMIONIC POWER MODULE EVALUATION	43
1.2.1 TASK V. SYSTEM STUDIES	43
1.2.2 TASK VI. TAM MODULE DEVELOPMENT	44
A. Converter No. 218 (CVD Silicon Carbide Converter No. 1): CVD Fluoride Tungsten (As Deposited) Emitter, Nickel Collector	44
B. Converter No. 228 (CVD Silicon Carbide Converter No. 3): CVD Tungsten (As Deposited) Emitter, Nickel Collector	45
C. Half Scale CVD Silicon Carbide Converter	45
D. High-Temperature Gas and Oil-Fired Furnace	47
1.2.3 TASK VII. COAL-FIRED TAM TEST UNIT	49

2.0	PART TWO: NASA-OAST/JPL TASKS	51
2.1	THERMIONIC CONVERTER EVALUATION	51
2.1.1	TASK VIII. HIGH-TEMPERATURE CONVERTER EVALUATION	51
	A. Converter No. 223: (JPL No. 2): Molybdenum Emitter, Tungsten Oxide Collector	51
	B. Converter No. 227: (JPL No. 1) Molybdenum Emitter, Niobium Collector	58
	C. Converter No. 234: (JPL No. 3): Molybdenum Emitter, Molybdenum Oxide Collector	61
2.1.2	TASK IX. ADVANCED CONVERTER STUDIES	62
	A. Particle Thermionic Converter	62
2.1.3	TASK X. POSTOPERATIONAL DIAGNOSTICS	63
	A. LaB ₆ -Re Bond Test	63
2.2	CYLINDRICAL CONVERTER DEVELOPMENT	68
2.2.1	TASK XI. CYLINDRICAL CONVERTER COMPONENT DEVELOPMENT	68
2.2.2	TASK XII. CORRELATION OF DESIGN INTERFACES	69
	REFERENCES	75

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Note: Roman Numerals Designate Level at Which Tasks are to be Reported

JPL CONTRACT NO. 955009
WORK BREAKDOWN STRUCTURE

Note Roman Numerals Designate Level at which Tasks are to be Reported.

INTRODUCTION AND SUMMARY

The Advanced Thermionic Technology Program at Thermo Electron Corporation is sponsored by the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA) via the Jet Propulsion Laboratory (JPL).

The primary long-term goal of the DOE effort is to improve TEC performance to the level that thermionic topping of fossil fuel steam powerplants becomes technically possible and economically attractive. An intermediate goal is to demonstrate an in-boiler thermionic module in the early 1980's. A short-term goal is the demonstration of the reliability of thermionic operation in a combustion environment.

The focus of the JPL program is to develop thermionic conversion technology appropriate for nuclear electric propulsion (NEP) missions. These missions require operation at collector temperatures substantially higher than those associated with terrestrial applications.

The DOE and JPL tasks for developing thermionic energy conversion (TEC) are complementary and synergistic. Converter performance improvement is an area in which one agency's program supports the effort of the other.

This report covers progress made during the three-month period from October through December 1979. During this period, significant accomplishments include:

DOE PROGRAM

- Demonstration of over 3600 hours of stable operation (Quarter Scale Silicon Carbide Converter No. 1) in a combustion environment at emitter temperatures at, or above, 1600 K. This test is continuing.
- Calculation of a complete current density-voltage characteristics in the power quadrant which includes both double valued sheath effects at the emitter and the spatial distribution of electron temperature in the interelectrode plasma.
- Successful operation of Converter No. 222 with a cesium-graphite reservoir.

JPL PROGRAM

- Performance data have been obtained on three planar variable spaced converters with molybdenum emitters (Converter Nos. 223, 227 and 228).
- System calculations indicate that long term thermionic performance demonstrated at Thermo Electron should yield a power system specific mass less than 22 kg/kWe.

1.0 PART ONE: DOE TASKS

1.1 THERMIONIC AND MATERIAL RESEARCH AND TECHNOLOGY

1.1.1 TASK I. SURFACE AND PLASMA INVESTIGATIONS

The objective of this task is to support the development of thermionic energy converters by providing experimental data and analyses relating to plasma characteristics and electrode properties.

A. Surface Characterization Chamber Experiments

An additional manipulator assembly was designed and constructed for use when LEED experiments are performed or when high sample temperatures are necessary (see Figure 1). The manipulator is designed so that nearly complete viewing of the LEED screen is possible. The sample holder is fastened to the manipulator with a nut so that the bombardment filament can be securely positioned 1 mm from the sample. Thus, space charge effects are negligible, and emission currents of 3 A at 1000 V can be drawn. Large emitter assemblies (2 cm diameter, 1 cm thick) have been heated to 2400 K with this manipulator. The hook-type manipulator (TECO Progress Report No. 35) will be used when many samples are inserted from the vacuum interlock and moderate heating (< 2000 K) is necessary.

Figure 1. Low Profile Sample Manipulator for the Surface Characterization Chamber

In the previous progress report, a graph was presented which showed the $W(100)$ single crystal work function versus Zr/W and Zr/O ratios for a 1 L (10^{-6} torr-sec) oxygen dose. This graph is shown in Figure 2 together with a similar graph for a 10 L oxygen dose. There is a striking similarity in the curves for the 1 L and 10 L O_2 cases. This similarity suggests that the minimum work function of 2.73 eV for 1 L O_2 cannot be further lowered by the addition of more oxygen. In fact, the work function is not very sensitive to the amount of oxygen initially adsorbed since the 1800 K flash after the oxygen and zirconium adsorption will desorb any extra oxygen which is not bound to the surface by the zirconium. It is significant that for both oxygen doses the minimum work function occurs for $Zr/W = 0.78$ and $Zr/O = 0.39$. These Zr/W and Zr/O ratios thus become the coverages desired for the bulk diffusion experiments.

The data in Figure 2 illustrate the "surface method" of forming the low work function surface (i.e., no bulk diffusion is involved). It is desirable to form the low work function surface by a "bulk diffusion method" as described by Danielson and Swanson.⁽¹⁾ The emitter then becomes a bulk source of both zirconium and oxygen and the surface can be continually replenished.

Figure 2. Work Function of Zr-O-W versus Zr/W and Zr/O for Single Crystal W(100) for 1L and 10L Oxygen Exposures

The Zr/W and Zr/O ratios given for minimum work function with "surface method" should also give the minimum work function for the "bulk diffusion method."

The "bulk diffusion" method was first employed for CVD W(100) substrates. This method involves repeated cycles of Zr deposition, 1500 K heating in oxygen, and 2100 K heating in vacuum. The work function and the Zr/W and Zr/O ratios for one such cycling sequence are shown in Figure 3. The initial variations arise because the zirconium dosing was omitted for Run Nos. 2 and 4. The final work function after 16 cycles is 3.0 eV, and the Zr/W ratio is 0.69, lower than the desired 0.78. Additional sequences of 6 cycles and 3 cycles (starting with a 2400 K flash) yielded final work functions of 3.13 and 3.16 eV, respectively. An interesting fact was that the work functions after only one cycle were the lowest obtained for that sequence. The explanation for final work functions higher than 2.7 eV may be that diffusion in the grain boundaries may predominate over diffusion through the single crystal grains.

Bulk diffusion cycles and variations were performed on single crystal W(100), again with minimum work functions of 3.0 eV. The high final work function may

Figure 3. FERP Work Functions, Zr/W and Zr/O, Versus Cycle Number for CVD W(100)

be due to a slight misorientation of the crystal. The orientation of the crystal will be accurately determined by back x-ray diffraction.

Some experiments with carbon deposition were performed. Carbon was deposited on a W(100) surface after a 1.5×10^{-3} torr-sec exposure to CH_4 with the sample held at 1800 K. The Auger coverages were W-71%, C-28%, and O-1%. The FERP work function of this carbon-covered surface was 4.68 eV, which is the same as clean W(100). This indicates that a substantial carbon coverage does not change the work function of W(100). The carbon atoms must be arranged so that no C-W dipole moment exists perpendicular to the surface.

B. Converter Theory

Because of its simplicity, the monoenergetic beam approximation has been used to study the space charge problem in the sheath coupling the electrode to the plasma. With this approximation, the conditions for the formation of a double sheath can be expressed as:

$$j = 1 + \rho_i \left(\frac{m}{M} \right)^{1/2} a^{1/2} - \frac{\rho_e}{\sqrt{4\pi c}} e^{-c\psi_p} \quad (1)$$

$$\psi_p^{1/2} + \frac{\rho_e}{2c} \left(1 - e^{-c\psi_p} \right) + \rho_i a \left[1 - \left(1 + \frac{\psi_p}{a} \right)^{1/2} \right] = 0 \quad (2)$$

$$\rho_e = \rho_i - \psi_p^{-1/2} \quad (3)$$

$$a = \frac{\rho_i}{2c\rho_e - \psi_p^{-3/2}} \quad (4)$$

The definitions of the symbols are given in Table I. The relation between j and ψ_p or between ψ_p and ρ_i can be obtained from these equations. The results are plotted in Figures 4 and 5. The results of the Half-Maxwellian model and a typical plasma solution are also plotted on these figures. The intersections of the plasma solution and the sheath solution in these figures indicate the required matching conditions between the sheath and the plasma. The results of the Half-Maxwellian sheath model and the plasma calculation intersect at $\psi_p = 0.8$, $\rho_i = 1.6$ and $\psi_p = 0.7$, $j = 0.43$. The intersection points of the monogeneretic beam sheath model and the plasma calculation are $\psi_p = 1.6$, $\rho_i = 2.26$ and $\psi_p = 0.35$, $j = 0.395$. The Half-Maxwellian sheath model predicts a good match between the sheath and the plasma. The monoenergetic beam model fails to predict the formation of a double sheath because of the mismatch between the sheath and the plasma.

TABLE I
GLOSSARY OF SYMBOLS

a	Dimensionless Ion Cutoff Energy
c	Dimensionless Electron Temperature
d	Interelectrode Spacing
j	Dimensionless Current Density
m	Electron Mass
M	Ion Mass
T_C	Collector Temperature
T_E	Emitter Temperature
T_R	Reservoir Temperature
ϕ_C	Collector Work Function
ψ_p	Dimensionless Plasma Potential
ρ_e	Dimensionless Electron Density
ρ_i	Dimensionless Ion Density

Figure 4. Comparison of Half-Maxwellian Model and Monoenergetic Beam Model Matching Parameters

Figure 5. Comparison of Half-Maxwellian Model and Monoenergetic Beam Model Matching Parameters ψ_p and ρ_i .

The sheath analysis program has been combined with the plasma program. The calculation of the current-voltage characteristics of a thermionic converter has been extended to the obstructed region by using the concept of a virtual emitter which appears after the formation of a double value sheath between the electrode and plasma. With this approach, the boundary conditions and the governing equations of the plasma in the obstructed region are the same as those in the saturated region. This analysis is used to maintain the match between the sheath and the plasma as the output current changes.

A typical calculated I-V curve is shown in Figure 6. It indicates that after the formation of a double sheath the J-V curve behaves as the Boltzmann line (i.e., an exponential function). However, most of the experimental data indicate that the slope of the J-V curve in this region is steeper than the Boltzmann line. Thus, this analytical result is not fully consistent with experimental data. The analyses also indicate that in the obstructed region: 1) the potential and electron temperature distributions are almost independent of current density, and 2) the charged particle density

Figure 6. Calculated Current Density-Voltage Characteristic

decreases as the current density decreases. Since the electron temperature distribution is constant, the heat flux to the collector is constant. This result is consistent with the experimental data in the next section.

1.1.2 TASK II. LOW-TEMPERATURE CONVERTER DEVELOPMENT

The objective of this task is to develop thermionic diodes with improved performance at low collector temperatures (i.e., 500-900 K). Converter characteristics will be measured as a function of emitter temperature, collector temperature, cesium pressure, interelectrode spacing and, if applicable, additive gas pressure.

A. Converter No. 215: Heat Flux Diode: Tungsten Emitter, Nickel Collector

During this reporting period, collector heat flux measurements were made at an emitter temperature of 1700 K. This emitter temperature allowed heat flux measurements to be made entirely in the power producing region. A typical cesium family at $T_E = 1700$ K, $T_C = 900$ K, and $d = 0.25$ mm is given in Figure 7. As was the case with measurements made at an emitter temperature of 1400 K, and consistent with other studies,^(2,3,4) the electron heating rate was found to be constant over a range of current densities from 4.0 to 9.0 A/cm². The auxiliary heater power density versus converter current density is given in Figure 8 for two determinations made at $T_E = 1700$ K, $T_C = 850$ K, $T_R = 577$ K, and $d = 0.25$ mm.

Figure 7. Cesium Family for Heat Flux Diode (Converter No. 215)

Figure 8. Heat Flux Data as a Function of Current Density at an Emitter Temperature of 1700 K and a Collector Temperature of 850 K.

The collector electron heating rate was measured over a range of collector work functions. Different work functions were obtained by moving along the ϕ_c versus T_C/T_R curve by varying T_C and holding T_R constant. Measurements were made at collector temperatures of 750, 800, 850, and 900 K. Current voltage characteristics, parametric in collector temperature, are given in Figure 9. As can be seen from this figure, the output voltage of the diode increases as the ratio of T_C/T_R approaches that value which corresponds to a minimum ϕ_c (see Figure 10).

The results of the heat flux determinations made at the various collector temperatures are listed in Table II. The difference of the measured collector electron heating rate minus the collector work function (as determined by the retarding plot method) over the range of experimental conditions was an average of 0.54 ± 0.04 eV. This value corresponds to an electron temperature of 3100 K. A graphical representation of these data is given in Figure 10. In this figure the collector work function as determined by retarding plots and the electron heating rate is plotted against the ratio,

Figure 9. Collector Family for Heat Flux Diode (Converter No. 215)

Figure 10. Correlation of Collector Heating Rate and Collector Work Function Measurements.

TABLE II
COLLECTOR HEAT FLUX DATA PARAMETRIC IN
COLLECTOR TEMPERATURE

$$T_E = 1700 \text{ K}$$

$$T_R = 577 \text{ K}$$

$$d = 0.25 \text{ mm}$$

T (K)	T_C/T_R	ϕ_C^* (eV)	ϕ_C^{**} (eV)
750	1.30	1.94	2.39
800	1.39	1.84	2.37
850	1.47	1.78	2.29
900	1.56	1.70***	2.27

* Average of Three Retarding Plot Measurements.

** Average Value for Collector Heating Rate.

*** Extrapolated from ϕ_C Versus T_C/T_R Plot.

T_C/T_R . As can be seen, the heat flux measurements closely follow the retarding plot determinations.

The collector electron heating rate was also measured at several spacings. These measurements were made at an emitter temperature of 1700 K, a collector temperature of 850 K, and a cesium reservoir temperature of 577 K. The ratio of collector temperature to cesium reservoir temperature was 1.47, which corresponds to a retarding plot work function of 1.78 eV. A spacing family at these conditions is shown in Figure 11. The results of these measurements are detailed in Table III and shown graphically in Figure 12. The curve in Figure 12 shows a pronounced increase in collector electron heating with decreasing interelectrode spacing. If the collector work function is assumed to be independent of spacing, this result implies an increase in electron temperature from T_E 2400 K at $d = 1.50$ mm to T_E 3500 K at $d = 0.125$ mm.

A leak which developed at the emitter to sleeve weld prevented further experiments with this diode. A new heat flux diode will be designed and fabricated during the next reporting period.

Figure 11. Spacing Family for Heat Flux Diode (Converter No. 215).

Figure 12. Collector Heat Per Electron as a Function of Spacing.

TABLE III
COLLECTOR HEAT FLUX DATA PARAMETRIC IN
INTERELECTRODE SPACING

$$T_E = 1700 \text{ K}$$

$$T_C = 850 \text{ K}$$

$$T_R = 577 \text{ K (2 torr)}$$

$$T_C/T_R = 1.47$$

$$\phi_C = 1.78 \text{ eV (from retarding plots)}$$

d	p.d	Q
(eV)	(mm-torr)	(eV)
1.50	3.00	2.21
1.00	2.00	2.23
0.50	1.00	2.25
0.25	0.50	2.31
0.125	0.25	2.39

B. Converter No. 225: CVD Tungsten (As Deposited)
Emitter, Nickel Collector

This planar, variable spaced research converter duplicates the emitter and collector surfaces used in the flame heated diodes with CVD silicon carbide hot shells. Optimized performance characteristics for emitter temperatures ranging from 1400 to 1700 K are shown in Figure 13. The barrier index of 2.10 eV corresponds well with the performances of the hot shell converters.

In addition, the converter performance was studied at an emitter temperature of 1650 K. Optimized characteristics at several collector temperatures (from 900 to 1100 K) are shown in Figure 14.

C. Converter No. 226: CVD Electropolished Tungsten
Emitter, Nickel Collector

A standard variable spaced research converter with a CVD electropolished tungsten emitter and a nickel collector was fabricated and tested. Fully optimized performance characteristics at various emitter temperatures are shown in Figure 15. At an emitter temperature of 1700 K, the barrier index (at 5 A/cm^2) was 2.06 eV.

Figure 13. Optimized Performance (Spacing, Cesium Pressure, and Collector Temperature) for Converter No. 225 at Emitter Temperatures of 1400, 1500, 1600, and 1700 K.

Figure 14. Optimized Performance (Spacing and Cesium Pressure) for Converter No. 225 as a Function of Collector Temperature for an Emitter Temperature of 1650 K.

Figure 15. Fully Optimized (Spacing, Cesium Pressure, and Collector Temperature) Performance of Converter No. 226 at Emitter Temperatures of 1400, 1500, 1600, and 1700 K.

The performance of the converter at an emitter temperature of 1650 K was studied at several collector temperatures (see Figure 16). A barrier index of 2.06 eV at $T_C = 900$ K degraded to 2.46 eV at a collector temperature of 1100 K.

Figure 16. Optimized Performance (Spacing and Cesium Pressure) for Converter No. 226 as a Function of Collector Temperature at an Emitter Temperature of 1650 K.

1.1.3 TASK III. ENHANCED MODE CONVERTER EXPERIMENTS

The objective of this task is to formulate and evaluate thermionic converter configurations which have the potential of operating more efficiently than the conventional ignited mode diode. In the ignited mode, the mechanism for supplying the ions for space charge neutralization is not efficient. Other techniques which allow the converter to operate in the unignited mode (e.g., those utilizing auxiliary discharge regions and surface contact ionization electrodes) should be more efficient in producing ions and, hence, more efficient in converting heat into electricity. Close-spaced devices that do not require ions should also be more efficient than ignited mode diodes. In the ignited mode, structured electrodes offer the possibility of significantly reducing the plasma losses. Several types of enhanced mode converters will be investigated experimentally.

Dr. Ivor Brodie of SRI International has reviewed the emitter-ionizer electrode configuration desired for the particulate ionizer surface ionization triode (PISIT). He has indicated that SRI International could

probably fabricate such an electrode if boron nitride could be used as the insulation between the emitter and ionizer islands. A sample of boron nitride will be compatibility tested at converter temperature and cesium pressure. The apparatus for this test has been designed and the experiment will be performed during the next reporting period.

1.1.4 TASK IV. COMPONENT HARDWARE DEVELOPMENT

The objective of this task is to develop converter hardware suitable for operation in a combustion atmosphere such as would be encountered in a thermionic-topped fossil fuel powerplant. Although the effort includes considerable materials evaluation, the focus is on the fabrication and testing of hot shell-emitter sub-assemblies utilizing chemical vapor deposition (CVD) of composite silicon carbide/graphite/tungsten structures.

A. Alloy Hot Shell Development

The testing of alloy hot shells in the Simulated Furnace continued during this reporting period. In this furnace, the domes of the hot shells are exposed to products of combustion of a liquid hydrocarbon at 1475 K. The interiors of the shells are evacuated by an ion pump. The furnace temperature and the interior vacuum of each shell are recorded on a strip chart recorder. The accumulated test hours on the specimens are shown in Table IV.

TABLE IV
SIMULATED FURNACE TESTS
(8 January 1980)

Test Port No.	Hot Shell	Test Hours	Comments	Date of Initiation
1	446 CRES Cr-Ni Slurry Sinter	3829	Leaktight	20 Nov 1978
3	446 CRES Plasma Arc Sprayed with Cr_2O_3	9303	Leaktight	31 Oct 1977
4	RA333	2197	Leaktight	31 Aug 1979
5	446 CRES Plasma Arc Sprayed with Nichrome	9303	Leaktight	31 Oct 1977
6	INCONEL 671	3524	Leaktight	8 Mar 1979

Clock Reference 26307

B. CVD Hot Shell-Emitter Development

1) Hot Shell Fabrication

During this reporting period, nine two-inch diameter and seven one-inch diameter CVD emitter-hot shell structures were fabricated. All units were leak tight. The two-inch composite emitter-hot shell structures were deposited on graphite substrates machined within an accuracy of ± 0.005 in. on the inside radii of the hemispherical dome. The profile of the CVD tungsten coating on the inside ranged ± 0.008 in. This combined variation in graphite machining and tungsten thickness makes it difficult to obtain a constant emitter-collector spacing over the electrode surface. As a result all future graphite shells will be machined with an accuracy of ± 0.002 in. on the inside radius of the hemispherical dome using a tracer lathe and templates. In addition, the CVD tungsten thickness profile variation has been reduced to ± 0.003 in. by optimizing the injector to shell spacing. It is likely that further improvements can be accomplished refining the injector design (hole size, spacing, and direction).

2) Microstructured Tungsten Deposits

Dendrite tungsten structures have been deposited on both graphite shells and tungsten slugs. The procedure was to initially deposit tungsten for 1 hour using the standard parameters. This would result in a smooth, leak tight tungsten deposit. Without interrupting the CVD run, the WF_6 flow was reduced and the chamber pressure was increased for a period of 4 hours. Some of the tungsten microstructures are shown in Figures 17 and 18.

3) Composite Emitter-Hot Shell Test Program

A program is planned to combustion test only the composite emitter-hot shell structures. A test stand has been designed to allow the structure to be inserted and removed quickly from the furnace. This will permit inspection of the silicon carbide surface and flange bond as well as leak checking. The test stand components are being fabricated.

4) TRW Tests

Samples of silicon carbide, tungsten, and composite emitter-hot shell structures have been sent to TRW for analysis. The structures will be examined for evidence of any reaction between the three materials of the composite shell (SiC, W, 2nd graphite) before and after high-temperature operation. In addition, flyash erosion tests will be performed.

50 X

200 X

1000 X

7912-16

Figure 17. CVD Fluoride Tungsten on Graphite Substrate (Deposited at Pressure of 180 torr).

7912-17

30 X

400 X

1000 X

Figure 18. CVD Fluoride Tungsten on Graphite Substrate.

C. Integral Cesium Reservoir Converter No. 222:
Tungsten Emitter, Nickel Collector, Cesium-Graphite
Reservoir

The testing of Converter No. 222 continued during this reporting period. After the cesium reservoir was pinched off, tests were made to determine whether the cesium-graphite reservoir could maintain the desired cesium pressure in the diode.

The emitter temperature was maintained at 1700 K and the collector temperature was set at 750 K. Current density versus voltage characteristics were taken, as the temperature of the cesium-graphite reservoir was changed. The equilibration times required to form the cesium-graphite compounds⁽⁵⁾ in the reservoir are indicated in Figure 19. The correspondence of the temperature of the cesium-graphite reservoir to the temperature of the liquid cesium reservoir at a given cesium pressure is shown in Figure 20.

Testing on this converter is completed. The ability of the cesium-graphite reservoir to vary and to maintain the cesium vapor pressure in the converter has been demonstrated.

Figure 19. Comparison of Cesium-Graphite and Liquid Cesium Reservoir Temperatures to Obtain a Given Cesium Vapor Pressure.

Figure 20. Current Density-Voltage Characteristics as a Function of Equilibration Time.

1.2 THERMIONIC POWER MODULE EVALUATION

1.2.1 TASK V. SYSTEM STUDIES

The objective of the system studies task is to identify the design approaches to integrate thermionic energy converters into fossil fuel central station powerplants in the most cost effective manner. The results of these studies will help orient the design of the thermionic array module (TAM) being developed in the next Task VI.

Stone and Webster Engineering Corporation has completed their study of a coal-fired thermionic topped central station powerplant. This report received DOE patent clearance on December 12, 1979. It will be issued as a topical report in the near future.

1.2.2 TASK VI. TAM MODULE DEVELOPMENT

The objective of this task is to develop combustion-heated TAM thermionic converters, individually and in small arrays, which are prototypic for topping a central station powerplant. Devices with both alloy and silicon carbide hot shells will be made and tested. In order to define the transient thermal and electrical characteristics of a TAM, a four-converter array will be constructed and tested.

A. Converter No. 218 (CVD Silicon Carbide Converter No. 1): CVD Fluoride Tungsten (As Deposited) Emitter, Nickel Collector

This converter continued on life test at an emitter temperature between 1600 and 1630 K. It has operated for 3666 hours as of December 31. The performance has remained stable throughout the test. The barrier index is 2.1 eV while the power output at 1600 K is 2.1 W/cm². The converter was thermal cycled four more times to room temperature during this reporting period (for a total of eight thermal cycles to room temperature during this test). The life test of this converter is continuing.

B. Converter No. 228 (CVD Silicon Carbide Converter
No. 3): CVD Tungsten (As Deposited) Emitter,
Nickel Collector

This CVD silicon carbide converter is identical to Converters Nos. 218 and 221. It has been outgassed, cesiated, and tested during this reporting period. The performance was almost identical to that of CVD Silicon Carbide Converter No. 1. The barrier index was 2.1 eV at an emitter temperature of 1600 K and the measured power density was 2.1 to 2.2 W/cm². The optimum collector and cesium reservoir temperatures were 900 K and 580 K, respectively. As of December 31, the converter was operated for 1416 hours at an emitter temperature ranging between 1600 and 1650 K. This converter has been thermal cycled to room temperature four times. This life test is continuing.

C. Half Scale CVD Silicon Carbide Converter

A half scale CVD silicon carbide converter has been designed and construction of the converter is underway. The converter design is shown in Figure 21. The composite emitter-hot shell structure is identical to those of

Figure 21. Half-Scale CVD Silicon Carbide Converter Design.

of the quarter-scale CVD silicon carbide converters except for the size. The half scale emitter is 7.6 cm long and 5 cm in diameter. The outer layer is CVD silicon carbide, the middle layer is graphite, and the inner layer (the emitter) is CVD tungsten (as deposited). The active area of the half scale emitter is 36.6 cm^2 . The collector for this converter is made from nickel and is air cooled.

The half scale design is close to being prototypic in that the cesium tubulation, the ceramic insulator, and the emitter flange are contained almost entirely within the emitter diameter. Final assembly of the converter and its furnace mounting fixture should be completed during the next reporting period.

D. High Temperature Gas and Oil Fired Furnace

Due to the steel flue liner in the Multi-Converter Furnace, the maximum emitter temperature that is safely obtainable for long periods is 1650 K. During the reporting period, a new furnace has been designed so that emitter temperatures of 1800 to 1850 K may be reached. The furnace has 9 inches of high-temperature fire brick for insulation.

There is no steel flue liner in the new design. The recuperator on the new furnace is equipped with a valve which allows for variable air flow there by adjusting the temperature of the preheat air. The furnace is fired by a flat flame burner that has dual fuel capabilities. Either natural gas or No. 2 fuel oil can be burned. The high-temperature furnace is being constructed in lieu of building the thermal gradient unit.

1.2.3 TASK VII. COAL-FIRED TAM TEST UNIT

The objective of this task is to prepare plans for a TAM coal-fired test unit. The preliminary design will be formulated by taking into consideration the results of the system studies and TAM module development. The TAM test unit design will be the smallest size consistent with a realistic simulation of the temperatures, heat fluxes, and slag conditions of a coal-fired steam powerplant.

The survey of available coal fired test furnaces is continuing. A cost estimate should be available during the next reporting period.

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2.0 PART TWO: NASA-OAST/JPL TASKS

2.1 THERMIONIC CONVERTER EVALUATION

2.1.1 TASK VIII. HIGH TEMPERATURE CONVERTER EVALUATION

The objective of this task is to characterize the performance of candidate emitters, collectors, and converter configurations at the high collector temperatures (900-1100 K) required for nuclear electric propulsion. Variable spaced, planar converters will be used for this task. Evaluation of each converter will include measurements of the output current density versus load voltage as a function of emitter temperature, collector temperature, interelectrode spacing, and cesium pressure.

A. Converter No. 223: (JPL No. 2) Molybdenum Emitter, Tungsten Oxide Collector

Fully optimized data have been obtained for Converter No. 223 at emitter temperatures of 1400, 1650, and 1700 K. Figures 22, 23, and 24 show the optimized converter performance at various spacings for the three emitter temperatures. At a current density of 5 A/cm² the barrier indices were 2.08, 2.16, and 2.16 eV at T_E = 1400, 1650, and 1700 K, respectively. The relatively

Figure 22. Current Density-Voltage Characteristics of Converter No. 223 at an Emitter Temperature of 1400 K for Optimized Cesium Reservoir Temperatures, Parametric in Interelectrode Spacing.

Figure 23. Current Density-Voltage Characteristics of Converter No. 223 at an Emitter Temperature of 1650 K for Optimized Cesium Reservoir Temperatures, Parametric in Interelectrode Spacing.

Figure 24. Current Density-Voltage Characteristics of Converter No. 223 at an Emitter Temperature of 1700 K for Optimized Cesium Reservoir Temperatures, Parametric in Interelectrode Spacing.

wide spacings of 0.50 to 1.00 mm and the increase in emitter saturation current with increasing collector temperature (previously reported in Progress Report No. 40) indicate that the tungsten oxide collector has a beneficial effect on the molybdenum emitter. The fully optimized converter performance is given in Figure 25.

Historically, heating a tungsten oxide collector to 850 K in a half torr of cesium for approximately 5 minutes has reduced the barrier index in similar converters. This reduction is attributed to a lowering of the collector work function and a decrease in the electrical resistivity of the oxide coating. This procedure was tried a number of times throughout the test of this diode. No appreciable reduction in the barrier index was apparent. The output of this converter is a characteristic of a tungsten oxide system operating in the preactivation or the postactivation stage. The minimum value of the collector work function as measured by the retarding plot method was 1.60 eV. Collector work function versus T_C/T_R data are given in Figure 26. After approximately 470 hours of operation, the diode developed a leak in the sapphire window this prevented further measurements.

Figure 25. Optimized Performance (Spacing, Cesium Pressure, and Collector Temperature) of Converter No. 223 at Emitter Temperatures of 1400, 1650, and 1700 K.

Figure 26. Collector Work Function versus the Ratio of Collector and Cesium Reservoir Temperatures.

B. Converter No. 227: (JPL Converter No. 1)
Molybdenum Emitter, Niobium Collector

A standard variable spaced research converter with a molybdenum emitter and a niobium collector has been fabricated and tested. Figure 27 shows the optimized (cesium reservoir temperature, collector temperature, and spacing) current-voltage characteristics at emitter temperatures of 1400, 1500, 1600, and 1700 K. The barrier index varies from a low of 2.20 eV at $T_E = 1400$ K to a high of 2.30 eV at $T_E = 1700$ K. The output power density was also studied as a function of collector temperature at an emitter temperature of 1650 K. Optimized cesium and spacing families for collector temperatures ranging between 900 and 1100 K are shown in Figure 28. At a collector temperature of 900 K the barrier index was 2.30 eV. This value increased to 2.40 eV at a collector temperature of 1100 K.

Figure 27. Optimized Performance (Spacing, Cesium Pressure, and Collector Temperature) of Converter No. 227 at Emitter Temperatures of 1400, 1500, 1600, and 1700 K.

Figure 28. Optimized Performance (Spacing, Cesium Pressure, and Collector Temperature) of Converter No. 227 at Emitter Temperature of 1650 K Parametric in Collector Temperatures from 900 - 1100 K.

C. Converter No. 231: (JPL Converter No. 3).
Molybdenum Emitter, Molybdenum Oxide Collector

A planar, variable spaced research converter with a molybdenum emitter and a molybdenum oxide collector has been fabricated. The diode has a sapphire window for visual observation of the discharge.

The collector was formed by subliming molybdenum in the presence of 8×10^{-6} torr of oxygen onto a niobium substrate. A twin surface, sublimed simultaneously, contained 1130 ppm of oxygen by weight. Performance of this converter will be compared to the performance of Converter No. 210 whose collector contained 3200 ppm of oxygen by weight. This converter has been outgassed and cesiated.

2.1.2 TASK IX. ADVANCED CONVERTER STUDIES

In the conventional ignited mode diode, transport losses due to ionization and coulombic and neutral atom scattering greatly reduce conversion efficiency. The objective of this task is to demonstrate improved thermionic converter performance by means of reduced potential loss in the interelectrode space. Based on previous studies, the particle thermionic converter (PTC) has been chosen for further investigations. Specifically, the electrical and thermal properties of PTC configurations will be tested as a function of particle composition and electrode spacing.

A. Particle Thermionic Converter

The potential for using magnesium oxide (MgO) in a particle converter is being investigated. Magnesium oxide is stable at high temperatures, however its uncesiated emission characteristics are poor. A variable spaced research converter with an MgO sprayed tungsten emitter is under construction. A guarded collector should ensure accurate cesiated MgO work function measurements. It is planned to test this converter in the next reporting period.

2.1.3 TASK X. POSTOPERATIONAL DIAGNOSTICS

The variable spaced planar converters built for JPL are deliverable items. However, if it appears advisable on mutual agreement between JPL and Thermo Electron, selected converters shall be opened for postoperational diagnostics after performance testing. The objective will be to identify the degradation mode, if any, and identify the probable mechanisms of formation.

A. LaB₆-Re Bond Test

The fabrication and Auger analysis of an LaB₆-Re bond were discussed in the last quarterly report. During this reporting period, a microprobe scan across a cross-sectional slice through the bond were taken. A photomicrograph of the bond with regions identified by numbers is shown in Figure 29. Region Nos. 1 and 2 are on the rhenium cup, Region Nos. 3 and 4 are the primary bonding regions, and Region Nos. 5 - 8 are the LaB₆ material. The tilt of the LaB₆ in the cup is apparently caused by initial formation of an Re-B liquid eutectic at a cup corner where more Re is available.

Figure 29. Photomicrograph (x15 magnification) of a Cross Sectional Slice Through a LaB₆-Re Bond.

The weight percent of the elements detected for Region Nos. 1-8 is shown in Table V. Boron is not listed because the microprobe is not sensitive to elements below mass number 11. The presence of large amounts of Na and some S, Cl, K, and Ca at interface Region No. 3 is puzzling because the surfaces were ultrasonically cleaned before the bond was formed. Apparently, these impurities are present in either the Re or the LaB_6 and diffuse to the interfacial region during heating.

The weight percent of La and Re as a function of region number is plotted in Figure 30. The Re content increases and the La content decreases as the beam is moved from Region No. 8 to Region No. 1, as expected. The unexpected result is that appreciable Re is present in Region No. 5, indicating that Re has diffused into the LaB_4 . Region No. 5 is most likely a combination of LaB_4 and Re, although a more complicated compound may exist. By contrast, no La has diffused into the Re cup (Region Nos. 1 and 2). Further tests of similar LaB_6 -Re bonds are planned.

TABLE V
CERAC LaB₆/Re BOND ANALYSIS

<u>POINT ANALYZED</u>	<u>ELEMENT</u>	<u>WEIGHT %</u>
1	Re	90.6
1	Al	9.4
2	Al	7.6
2	Re	92.4
3	Na	20.1
3	S	8.5
3	Cl	5.7
3	K	7.3
3	Ca	1.7
3	Re	56.7
4	Cr	0.3
4	La	34.2
4	Re	65.6
5	Sc	0.6
5	Cr	4.9
5	La	46.4
5	Re	48.1
6	Al	2.6
6	Si	2.2
6	Sc	1.1
6	Cr	1.0
6	La	93.1
7	Si	0.7
7	Cr	2.5
7	La	96.8
8	Sc	1.7
8	Cr	2.1
8	La	96.2

Figure 30. Weight Percent of La and Re as a Function of Region of the LaB_6 -Re Bond Sampled By Microprobe (from Table V).

2.2 CYLINDRICAL CONVERTER DEVELOPMENT

2.2.1 TASK XI. CYLINDRICAL CONVERTER COMPONENT DEVELOPMENT

The objective of this task is to develop the technology required to construct cylindrical converters, excluding the electrode surfaces. This task includes electrode insulation and seal-bellows subassembly.

The design of the seal-bellows subassembly is in progress. During the next reporting period, the design should be completed and construction of the subassembly should be begin.

An effort to fabricate cermet (alumina-niobium) insulators has been initiated. Thermo Electron laboratory notebooks have been reviewed and the required materials have been ordered.

2.2.2 TASK XII. CORRELATION OF DESIGN INTERFACES

The objective of this task is to provide technical coordination between Thermo Electron and other contractors as well as with government agencies, in order to assure overall compatibility of design, materials, and interfaces between the thermionic conversion and other subsystems.

In response to the data provided at the Nuclear Electric Propulsion Interface Working Group Meeting held September 27 and 28 at JPL, Thermo Electron has performed some system calculations. The power output of the system was redefined at this workshop as 120 kWe nominal. This was interpreted as 120 kWe at the beginning of life and 100 kWe at the end of life.

System parameters were estimated based on a reference design of the nuclear reactor power system⁽⁶⁾ as shown in Table VI. Two thermionic cases were calculated. For the first case the terminal efficiency of the thermionic converters was assumed to be 15.0%, for the second case the efficiency of 10.5% was used. The latter efficiency was calculated from measured thermionic converter power output data at Thermo Electron.

TABLE VI
THERMO ELECTRON SYSTEM COMPARISON

7910-28

SYSTEM PARAMETER	THERMIONIC		THERMOELECTRIC	
	PROGRAM GOAL	TECO DEMONSTRATED	REF*	SiGe DEMONSTRATED
ELECTRICAL OUTPUT (EOL), kWe	100	100	100	100
ELECTRICAL OUTPUT (BOL), kWe	120	120	120	120
TERMINAL EFFICIENCY, Percent	15.0	10.5	8.3	6.4†
CURRENT DENSITY, A/cm ²	10	6	-	-
CONVERTER HOT TEMPERATURE, K	1650	1650	1650	1300†
CONVERTER COLD TEMPERATURE, K	1000	900	900	-
RADIATOR TEMPERATURE, K	975	875	875	775†
SUBSYSTEM MASS, kg				
REACTOR, kg	440*	440*	440*	440*
SHIELD, kg	531*	540*	540*	540*
SPUTTER SHEILD, kg	122*	122*	166*	166*
CABLES, kg	66*	66*	4*	4*
SUBTOTAL, kg	1159	1159	1150	1150
CONVERTER, kg	287*	310*	372*	470*
RADIATOR, kg	307†	715†	1151†	1625†
TOTAL SYSTEM MASS, kg	1753	2184	2673	3245
SPECIFIC MASS, kg/kWe	17.5	21.8	26.7	32.5

*Based on JPL Handout of 27 Sept. 79, Fig. 4 (Pasadena).

†Based on radiator design in Thermacore Handout of 7 June 79 (Montreal) and

temperature was taken as 1650 K and the collector temperature was varied from 900 to 1000 K. The temperature difference between the radiator and the collector was assumed to be 25 K. The masses of the reactor, reactor shield, and sputter shield were taken from Reference 6. The mass of the thermionic converters was assumed to vary linearly with current density. The radiator mass was calculated based on the design shown in Reference 7. In this design, 23% of the collector heat rejection system mass was utilized in coupling the collector to the radiator. This fraction was taken to be independent of the radiator temperature. The remaining 77% of the heat rejection system mass was assumed to depend on the fourth power of the radiator temperature.

It would appear (cf. Table VI) that if the program goal of a thermionic converter with an efficiency of 15% is achieved, the projected system mass would be 1753 kg and the specific mass would be well within the mission requirements. If demonstrated thermionic performance is used, the system mass would be 2184 kg and the specific mass would be 21.8 kg/kWe, still an attractive value.

The performance of a reference thermoelectric system was estimated using a postulated 8.3% efficiency and 900 K cold junction temperature, resulting in a 26.7 kg/kWe specific mass. Similarly, the specific mass of a thermoelectric system using silicon-germanium with a thermal efficiency of 6.4%, operating between 1300 and 775 K⁽⁸⁾ was calculated to be 32.4 kg/kWe.

System mass estimates were made for collector temperatures ranging from 700 to 1100 K. The thermionic efficiency was calculated using the method of Hatsopoulos.⁽⁹⁾ The results of these calculations are shown in Figure 31, for three assumed thermionic performance levels. For these cases the optimum collector temperature ranges between 950 to 1000 K.

Figure 31. NEP System Mass versus Collector Temperature for Three Thermionic Performance Levels

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